Relativistic Electrons and Magnetic Storms: 1992-1995

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Abstract. This paper examines the relationship between relativistic electron enhancements at geosynchronous orbit and magnetic storms measured by the Dst index. We analyzed the 30 most intense relativistic electron events from 1992 to 1995 and all events that occurred in 1993. Every relativistic electron event was associated with a magnetic storm in the Dst index, but, magnetic storms could occur with no appreciable enhancement of the relativistic electron fluxes. By correlating the maximum electron flux in each event with the minimum Dst value we found that the maximum relativistic electron fluxes and maximum ring current intensity are roughly correlated but that there is considerable variation. These results suggest that the solar wind conditions that are necessary to generate a ring current response are also necessary to generate a strong relativistic electron response but that there is some additional factor, either in the solar wind or in the magnetosphere, that determines whether a given storm will produce relativistic electrons or not and how strong that response will be.

Introduction

The Earth's radiation belts are composed of magnetically trapped energetic charged particles. Two of the most important particle populations in the radiation belts are ring current particles, which are predominantly ions with energies of several hundred keV, and relativistic electrons, which have kinetic energies greater than about 0.5 MeV. Both populations are highly dynamic and both can be intensified during disturbed geomagnetic conditions. However, there is still considerable uncertainty about the physical mechanism (or mechanisms) that produce ring current and relativistic electron enhancements.

The Dst index is widely used as a measure of the strength of the ring current and is generally used to define the disturbed magnetospheric conditions that we call "magnetic storms". Magnetic storms are driven by strong energy input from the solar wind into the magnetosphere and hence into the ring current. The high degree of variability of the state of the ring current and the relatively frequent occurrence of magnetic storms is directly related to the high degree of variability in the solar wind conditions [see *Kamide et al.*, 1998 for a recent review]. Relativistic electrons are also enhanced during periods of strong energy coupling from the solar wind and, in particular, during high-speed solar wind streams [e.g. *Baker et al.*, 1998; *Blake et al.*, 1997] but the precise relationship between the two responses has not been thoroughly investigated.

Earlier efforts to relate relativistic electron fluxes to geomagnetic activity focused on predicting the electron flux based on a time series of the daily sum of the Kp index. *Nagai* [1988] showed a superposed epoch analysis of >2 MeV electrons and the Dst and Kp indices using the time of Dst minimum as the zero epoch. He found that the electron fluxes were minimum at the time of Dst minimum but related the variation to changes in the Kp index by means of a linear filter technique. *Baker et al.* [1990] extended the study of Nagai by applying linear prediction filters to a longer span of data, to more energies, and more input parameters (ΣKp, AE, and solar wind velocity). *Koons and Gorney* [1991] followed a similar procedure but used a neural network to relate ΣKp to the flux of >3 MeV electrons. All three studies related magnetic activity (a time sequence of ΣKp) to the log of the electron flux. However, *Kim and Chan* [1998] have shown that the dropout and recovery (but not subsequent enhancement) of the fluxes of relativistic electrons at geosynchronous orbit can be explained as an adiabatic response of the particle drift orbits to changes in the intensity of the ring current. They further showed that it is the log of the flux that scales with Dst. The relationship is apparent (but not noted) in Figure 2 of *Nagai* [1988] and helps explain why his linear filter was more successful at low fluxes than at high fluxes. (See also Figure 6 of *Baker et al.* [1990].)

Neither *Nagai*, *Baker et al.*, nor *Koons and Gorney* investigated the relationship between the occurrence of magnetic storms and relativistic electron enhancements. This question has recently been raised by *Sheldon et al.* [1997]. They propose that relativistic electrons may be accelerated in the cusp through a combination of cusp trapping and fluctuations in the solar wind dynamic pressure and that, therefore, magnetic storms (ring current enhancements) and relativistic electron events could occur independently of one another.

In this paper we compare a large number of individual events to determine the statistical relationship between both the occurrence and magnitude of storm-time enhancements of the ring current and relativistic electron responses. The period of study is from 1992 to 1995. In particular we focus on the year 1993 when a large number of well-defined relativistic electron enhancements were observed. We examine data from four energy channels (0.7-7.8 MeV) from the Energetic Spectrometer for Particles (ESP) detector [*Meier et al.*, 1996] on the geostationary satellite 1989-046. We determine the maximum fluxes observed in each energy range and investigate the statistical correlation between relativistic electron enhancements and magnetic storms indicated by the Dst index. In contrast to previous studies we focus on the peak geosynchronous electron fluxes measured during individual events as opposed to the continuous time history of electron flux variations.

Because of the importance of the relativistic electron environment for spacecraft operation and design, a word of caution is in order. The fluxes quoted in this paper have been calculated using nominal flux conversion factors. Therefore absolute flux numbers should be considered to have approximately a factor of 2 uncertainty. Efforts are underway to produce more accurate flux conversion factors. However, for this study we are primarily concerned with relative flux variations for which the nominal flux conversions are sufficient.

Observations

During the transition from solar maximum (1989) to solar minimum (1996) a prominent feature on the sun is the presence of solar coronal holes, regions of effectively 'open' magnetic flux which allow the solar wind to flow away from the sun at high velocities. When the coronal holes approach the solar equator the high speed streams can lie in the ecliptic plane and can impact on the Earth's magnetosphere. The coronal holes rotate with the sun so those that are relatively long-lived can reappear with the 27-day solar Carrington rotation period. It has been shown [e.g. *Baker et al.*, 1998; *Blake et al.*, 1997] that high speed streams that include a significant southward component of the interplanetary magnetic field (IMF B_Z<0) are associated with at least some of the observed relativistic electron enhancements in the radiation belts. Figure 1 shows 1-day averages of the flux of 1.8-3.5 MeV electrons measured at geosynchronous orbit between 1992 and 1995. The fluxes are plotted linearly which emphasizes the flux enhancements more than the (possibly adiabatic) flux dropouts and recoveries.

The insets in Figure 1 show X-ray images of the sun from the Yohkoh satellite [courtesy of the Yohkoh Data Archive Center]. One image is shown for each for four consecutive, 27-day solar rotations. The coronal hole shown in the images is believed to be responsible for the intense, periodic enhancement of relativistic electrons observed between days 230 and 350. Other coronal holes and other solar wind disturbances can be associated with the other events in Figure 1.

The purpose of this study, however, is to examine the relationship between relativistic electrons and magnetic storms independent of their relationship to solar wind conditions and to more fully characterize the relativistic electron conditions during magnetic storms. Figure 2 shows a more complete set of data from 1993. Here we plot 1-day averages of the relativistic electron fluxes measured in four energy channels from 0.7 to 7.8 MeV along with the Dst index. The 1-hour Dst index has been smoothed using a 25-hour running average. Thirty five relativistic electron enhancements were identified visually based on enhancements of the fluxes of 1.8-3.5 MeV electrons (panel 2). Those events are indicated in the figure by dotted vertical lines. Intensifications that produced multiple peaks within a given interval of enhanced fluxes were not marked as separate events. It is apparent from Figure 2 that when the fluxes of 1.8-3.5 MeV electrons are enhanced the fluxes of lower-energy electrons (0.7-1.8) are also enhanced but that the fluxes in the higher-energy channels may or may not show an enhancement. This is because the spectral slope also varies considerably from event to event.

Each of the relativistic electron events identified here is associated with a decrease in the Dst index indicating an intensification of the ring current. However, there is no simple relationship between the intensity of the two responses. For example the event beginning on day 155 was one of the most intense relativistic electron events observed in 1993 but the Dst index only reached a minimum value of -61 nT (minimum smoothed Dst≈-50 nT). In contrast the event beginning on day 335 had lower electron fluxes but a minimum Dst value of -117 nT (minimum smoothed Dst≈-77 nT). We also note that the most intense storm of 1993, which occurred on day 94, was one of four significant drops in Dst which was not accompanied by any significant enhancement of electrons above 1.8 MeV. Those four events are marked in Figure 2 with dashed lines.

Correlation with Dst

To further investigate the relationship between the magnitude of the events as measured by Dst and relativistic electron fluxes we assembled two related data sets. For the three years 1992-1995 we selected only the most intense events. Our selection criteria were (1) the maximum flux of 1.8-3.5 MeV electrons must exceed 5 (cm^2-s-sr-keV)$^{-1}$ and (2) the fluxes must drop to near zero between events. Events that occurred while Dst was still recovering from an earlier storm were not included in this analysis because the combined Dst produced by a new ring current injection added to a pre-existing ring current does not accurately the solar wind energy input. Relativistic electron events with multiple peaks were also counted as a single event. The 30 events that met this criteria are indicated in Figure 1. The number of days for which the flux exceeded 5 (cm^2-s-sr-keV)$^{-1}$ was 166 which represents 15% of the available daily averages in this three-year period.

In order to extend the statistical analysis to smaller relativistic electron events we selected a subset of the events identified in Figure 2. The events in 1993 were chosen based on (1) a clear electron response in the 1.8-3.5 MeV channel and (2) a clear Dst signature with a recovery to near zero. Again events that occurred during the recovery of an earlier storm were not included. Prior to day 150, when storms frequently overlapped in time, only 3 events met our criteria. The remainder of the 20 events occurred after day 150 when most storms had a clear and complete recovery (Figure 2). Seven of the events chosen from 1993 had maximum fluxes above 5 (cm^2-s-sr-keV)$^{-1}$ and therefore are also included in the 30 intense events from 1992-1995.

The minimum Dst value was determined for each of the 43 relativistic electron events in our study. One-hour, unsmoothed Dst values were used. Typically the minimum Dst occurred near the onset of, or prior to, the intensification of the relativistic electrons. This is to be expected since the relativistic electrons are known to peak several days after the onset of geomagnetic activity [e.g. *Paulikas and Blake*, 1979; *Nagai*, 1988].

Figure 3 shows the statistical relationship between the maximum flux of 1.8-3.5 MeV electrons for each event and the minimum Dst value reached during the event. The plot indicates a weak positive correlation between the strength of the ring current (more negative Dst) and the peak relativistic electron flux. As indicated by the two parallel dashed lines, there also appears to be both an upper and lower cutoff to the distribution of points. However the scatter in the distribution of points is large. For example, the plot would suggest that peak fluxes of 1.8-3.5 MeV electrons around 10 (cm^2-s-sr-keV)$^{-1}$ could occur in storms with minimum Dst values between -27 nT and -165 nT. The plot should not be used to determine expected flux levels for a given Dst because events were selected based on electron flux not Dst minima. Therefore, as in Figure 2, storms with no relativistic electrons are not included.

Table 1. Correlation between maximum electron flux and minimum Dst for four energy ranges.

Energy (MeV)	Dst Correlation (43 Events)	(42 Events)
0.7-1.8	.37	.21
1.8-3.5	.55	.31
3.5-6.0	.64	.36
6.0-7.8	.59	.34

Table 1 gives the correlation coefficients between the minimum Dst and maximum flux for each of the four ESP energy channels from 0.7 to 7.8 MeV. In addition we give statistics that exclude the event on days 132-138 of 1992 which had both the most intense flux of relativistic electrons (Figure 1) and the lowest value of Dst observed in this 3-year period. Although this is by no means a "bad data point" it clearly drives the magnitude of the correlation. The values in Table 1 confirm and quantify the impression one gets from Figures 2 and 3; that, while larger relativistic electron fluxes tend to be observed during larger storms, the relationship between ring current and relativistic electron intensifications is not simple. For completeness we also note that, based on all 43 events, the correlation between the log of the electron fluxes and Dst ranged from .30 for 0.7-1.8 MeV electrons to .46 for 6.0-7.8 MeV electrons, somewhat lower than the correlations with linear flux in Table 1.

It will be noted that our technique of selecting maximum electron fluxes and minimum Dst values compares events with a variety of lag times. We also performed a lagged cross correlation analysis of 1-hour averages of electron flux and Dst values for 1993. For 1.8-3.5 MeV electrons, cross correlations show a peak correlation coefficient of about .36 at a time delay of 1.75 days (42 hours). However, positive Dst values distort the results. Positive Dst values are caused by magnetopause compressions and are unrelated to the energy content in the ring current. When only negative Dst values are included in the lagged cross correlation the peak disappears and correlation coefficients between .30 and .32 are observed for all time delays between 1.75 and 3.75 days (42 and 90 hours). This indicates that a variety of lags between Dst and relativistic electron fluxes are in fact observed.

Conclusions

Our study covers the years 1992 to 1995 during the transition from solar maximum to solar minimum. This phase of the solar cycle is characterized by large coronal holes which span the solar equator and give rise to high speed streams in the solar wind. This interval was chosen for study because the conditions which were present in the solar wind produced a large number of relativistic electron enhancements. Based on analysis of the 30 most intense events that occurred from 1992 to 1995 along with all of the events that occurred in 1993 we reached the following conclusions.

- During 1993 every relativistic electron enhancement that we observed was associated with magnetic storm. Likewise, from 1992 to 1995 every intense (1.8-3.5 MeV electron flux > 5 (cm^2-s-sr-keV)$^{-1}$) relativistic electron enhancement was also associated with a magnetic storm.
- However, magnetic storms can occur with no associated enhancement of geosynchronous relativistic electron fluxes. In 1993 we observed four such events out of a total of 39 storms which is approximately 10%.
- We found a general tendency for relativistic electron events (flux maxima) to occur during more intense storms (smaller minimum Dst).
- However, the scatter is quite large. Dst can range over ≈140 nT for a given peak flux of 1.8-3.5 MeV electrons.

These observations put some interesting constraints on models for the acceleration of relativistic electrons. On one hand, the correlation between the strength of a magnetic storm and the strength of the relativistic electron event is low. In addition a small number (≈10%) of magnetic storms were observed without relativistic electron enhancements. On the other hand, relativistic electron events were only observed during magnetic storms and, there is some correlation between the strength of the two responses. Therefore, while we can conclude that the mechanism responsible for accelerating the relativistic electrons is not the same as the process that injects particles into the ring current we can also conclude that the two processes act at nearly the same time.

These results are not consistent with the proposals of *Sheldon et al.* [1997] that the ring current and relativistic electron enhancements are uncoupled or “bimodal” and that the source of the relativistic electrons acceleration is in the cusp. The results are more consistent with an acceleration mechanism that operates in the inner magnetosphere such as shock acceleration or wave-particle interactions [*e.g. Li et al.*, 1997]. In particular these observations leave open the intriguing possibility that the injection of ring current ions is somehow responsible for the generation of the waves which in turn accelerate the electrons. They also leave open the possibility that both the ring current injection and the relativistic electron enhancement are more directly driven by the solar wind conditions but that it is the pre-existing source population rather than the injection process that determines the magnitude of the two responses.

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Reeves, GRL, 1998

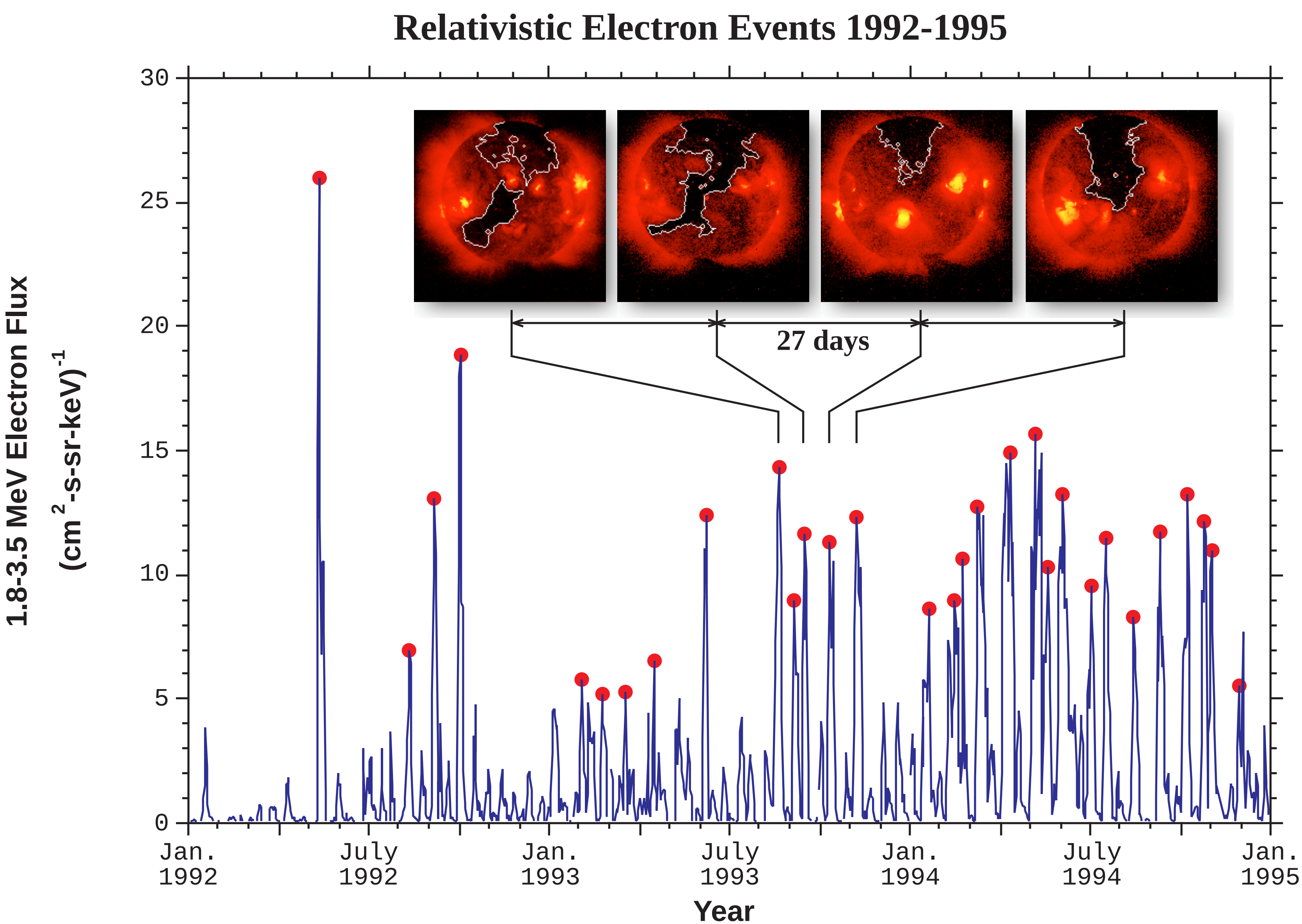

Figure 1. Relativistic electron fluxes (1.8-3.5 MeV) from the ESP detector on geosynchronous satellite 1989-046. The peak fluxes for the 30 most intense electron events are indicated with red dots. Solar X-ray images from the Yohkoh satellite for four events on days 230–350 show a clear association with a coronal hole source for high-speed solar wind streams.

Reeves, GRL, 1998

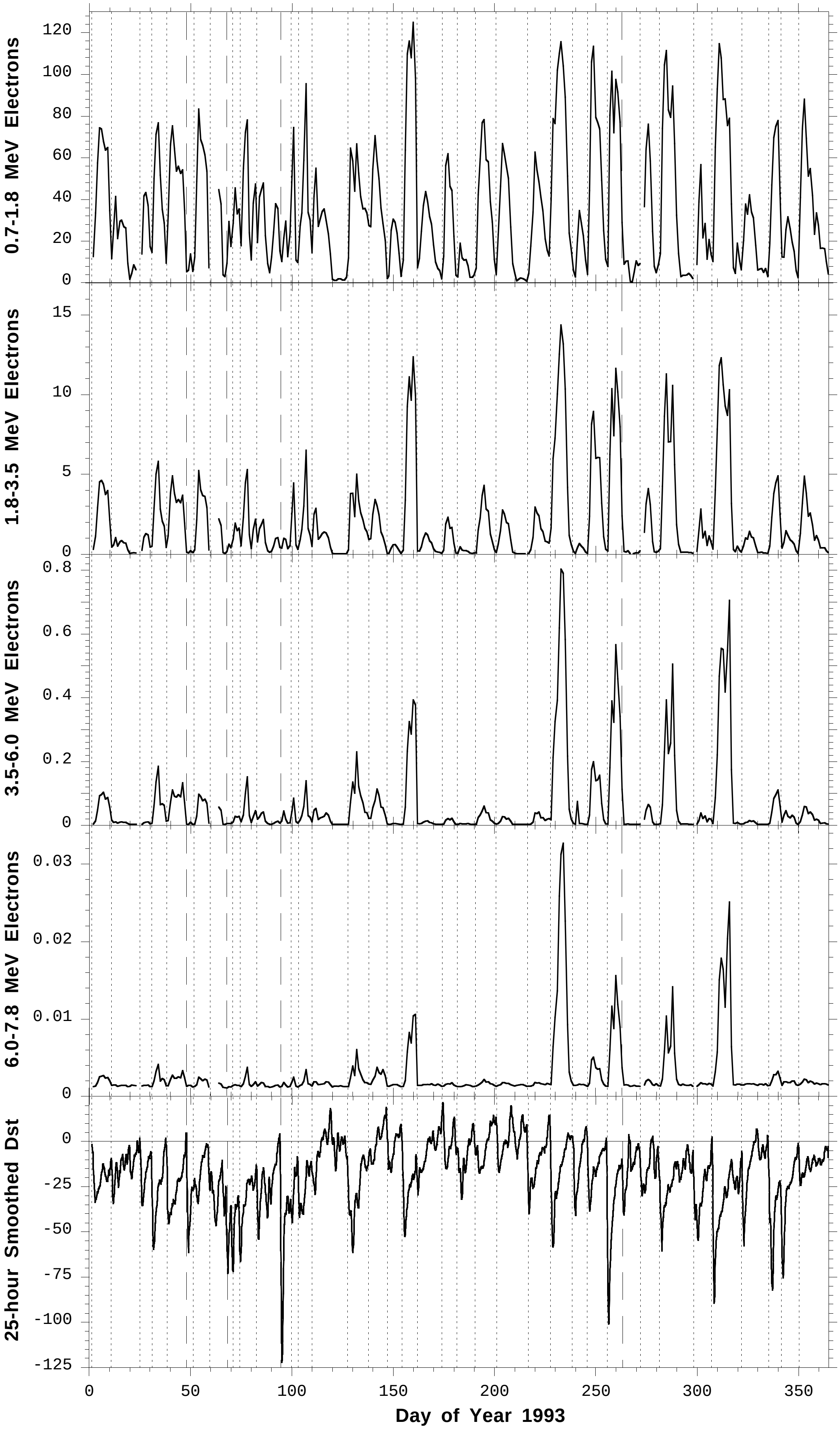

Figure 2. Relativistic electron fluxes (in [cm2-s-sr-keV]-1) in four energy channels from 0.7 to 7.8 MeV and the Dst index for 1993. Thirty five relativistic electron events of varying intensity are indicated with dotted lines. The four storms (Dst decreases) that occurred without significant electron fluxes are marked with dashed lines.

Reeves, GRL, 1998

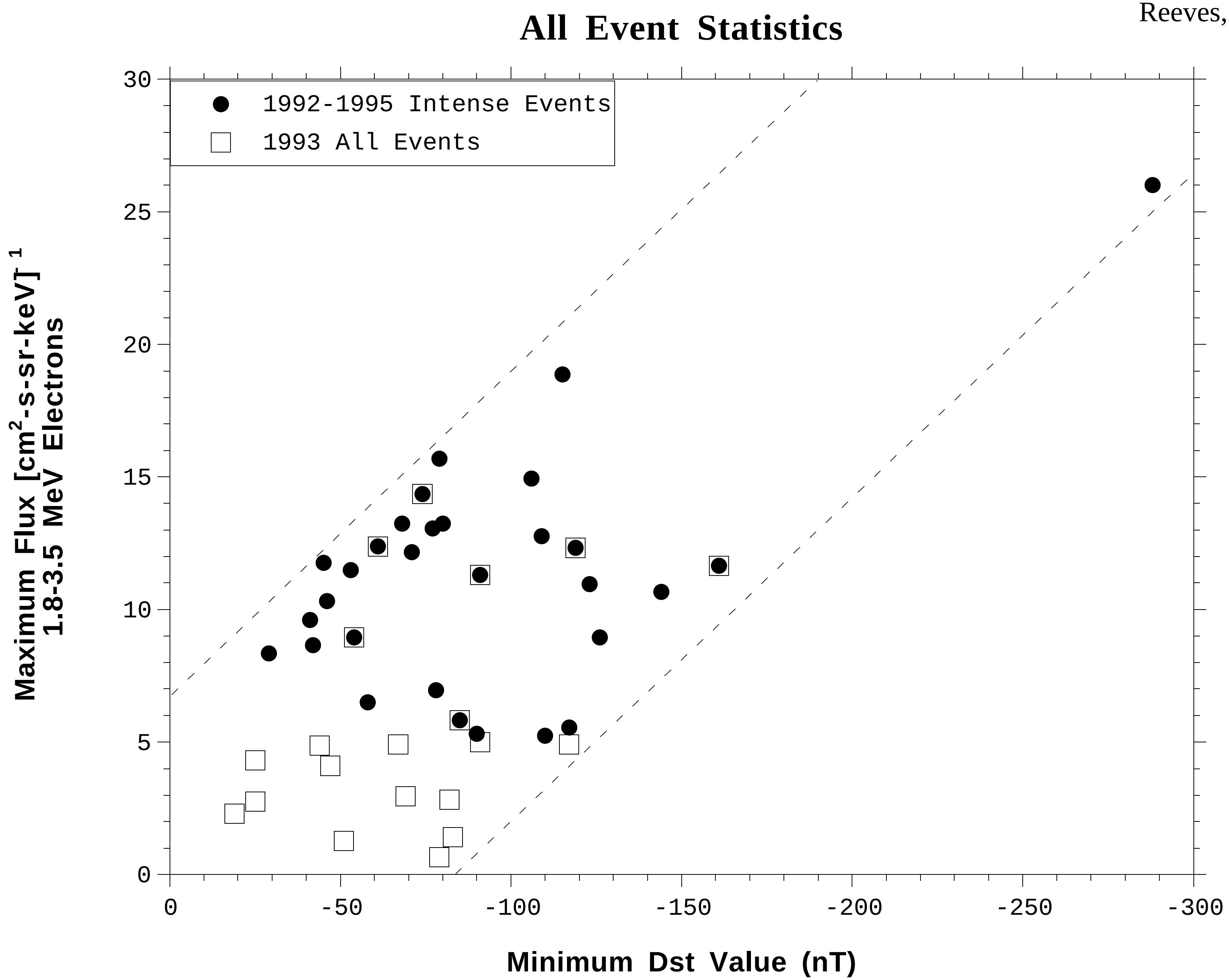

Figure3: Peak 1.8-3.5 MeV electron flux vs. minimum Dst. Dots represent the 30 most intense events from 1992 to 1995 (also shown in Figure 1). Open squares represent the 20 isolated events, both large and small, from 1993 (Figure 2). Seven events are in both data sets giving a total of 43 events. Although there is a large amount of scatter a rough correlation of larger electron fluxes with larger storms (smaller Dst) is observed.